MICROFOCUSING OF THE FERMI@ELETTRA FEL BEAM WITH A K-B ACTIVE OPTICS SYSTEM: SPOT SIZE PREDICTIONS

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FERMI@Elettra seeded FEL

FEL 1 from ~100 nm down to 20 nm - source distance (to spectrometer) 57.5 m
Divergence $\sigma(\mu\text{rad}) = 1.25\, \lambda(\text{nm})$ - Source dimension = 60 $\mu\text{m}$ (sigma)

FEL 2 from 20 nm down to ~4 nm - source distance (to spectrometer) 49.8 m
Divergence $\sigma(\mu\text{rad}) = 1.5\, \lambda(\text{nm})$ - Source dimension = 123 $\mu\text{m}$ (sigma)

PADReS

**FEL 1**
- Shutters
- BPM
- Plane mirrors
- BDA
- I0
- 2.5°
- 5°

**FEL 2**
- Shutters
- BPM
- Plane mirrors
- BDA
- I0
- 2.5°
- 5°

**Transverse Coherence Diagnostics**
- EIS Switching
- Monochromator
- Delay Lines
- Switching TIMEX-LDM
- KB System
- TIMEX
- Diproi
- LDM
- KB System
K-B active optic system - DiProI

End-stations need high flux - great demagnification

K-B system advantages
- Decoupling vertical and horizontal beam components
- Thick ellipsoidal mirrors with the great demagnification request are difficult to realize

K-B bendable system advantages
- Focalization of the 2 sources at different distance with the same couple of mirrors
- Difficult realization of thick elliptical mirror with this demanding demagnification
- Improvement of the FEL beam wave-front
K-B active optic system - DiProI

Profile surface characterization with Long Trace Profilometer

- LTP profile measurements 1mm step
- Best possible profile reached through the Adaptive Correction Tool software
- Measurements with Zygo interferometer and AFM - rms under specifications (<3A spatial range 2µm - 0.5mm)
- Proof of the system stability

K-B Vertical mirror - residual surface profile  
K-B Horizontal mirror - residual surface profile
Ray tracing simulations with Shadow code

**K-B vertical mirror at best focus**
(+2mm to the nominal focus)

\[
\text{FWHM}_{\text{ray-tracing}} = 18 \mu \text{m}
\]

**K-B horizontal mirror at best focus**
(-2mm to the nominal focus)

\[
\text{FWHM}_{\text{ray-tracing}} = 10.5 \mu \text{m}
\]
Focal spot measurements - DiProl

Phosphorus screen and PMMA ablation

First phase
- rough angle alignment
- optimized mirror bending
- best spot achieved on Phosphorus screen \( \text{FWHM}_{32\text{nm}} = 60 \times 70 \, \mu\text{m} \)

Second phase
- refine angle alignment
- optimized mirror bending
- best spot achieved on Phosphorus screen \( \text{FWHM}_{32\text{nm}} = 40 \times 42 \, \mu\text{m} \) - seen with PMMA ablation
\( \text{FWHM}_{32\text{nm}} = 15 \times 26 \, \mu\text{m} \)

Suggestion - Shadow predictions would be a lower limit of the optical system performance
PSF WITH FRESNEL DIFFRACTION


- PSF computation from surface metrology
- At any energy
- Approximations:
  - Work in scalar approximation
  - Computation using the meridional profiles (1Dimension)
- Work in grazing incidence
PSF WITH FRESNEL DIFFRACTION


ELECTRIC FIELD ON THE FOCAL PLANE OBTAINED BY THE CONSTRUCTIVE INTERFERENCE BETWEEN THE SPHERICAL WAVES GENERATED IN EACH POINTS OF THE MIRROR.

Kirchoff-Fresnel diffraction equation

$$U(P) = \frac{A e^{ikr_0}}{r_0} \int \int_{S} \frac{e^{iks'}}{s'} K(\chi) dS'$$

$$PSF(x) = \frac{\Delta R}{f \lambda L^2} \left| \sum e^{-i\frac{2\pi}{\lambda}(\sqrt{(x-x_p)^2+z_p^2}-z_p)\Delta l} \right|^2$$

In order to prevent mirror under sampling:

$$\Delta l \approx \frac{\lambda f^2}{2\pi R_0 r}$$

$$\Delta x \approx \frac{\lambda f^2}{\pi R_0 L}$$
PSF WITH FRESNEL DIFFRACTION


Two or more reflections

Double reflection

\[ E_h(x_h, z_h) = \frac{E_0 \Delta R}{L \sqrt{\lambda x_h}} \int_{f}^{f+L} \sqrt{\frac{x_p}{d_2}} e^{-\frac{2\pi i}{\lambda} (d_2 - z_p)} dz_p \]

\[ PSF(x) = \frac{\Delta R}{E_0^2 f \lambda L^2} \left| \sum E_h(x_h, z_h) e^{-i \frac{2\pi}{\lambda} (\sqrt{(x-x_h)^2 + z_h^2}) \Delta l} \right|^2 \]
Focal spot computation with Fresnel diffraction: FEL case

\[ u(x, z) = \frac{\omega_0}{\omega} e^{-j(kz - \Phi) - x^2 \left( \frac{1}{\omega^2} + \frac{jk}{2R} \right)} \]

\( R(z) = \) wavefront curvature radius

\( k = \frac{2\pi}{\lambda} \quad \Phi = \arctan(\lambda z / \pi \omega_0^2) \)

\[ E_h(x_h, z_h) = \frac{E_0 \Delta R}{L \sqrt{\lambda} x_h} \int_f^{f+L} \left( \frac{x_p}{x_h} \right) e^{-\frac{2\pi i}{\lambda} (d_2 - z_p)} \, dz_p \]

\[ PSF(x) = \frac{\Delta R}{E_0^2 f \lambda L^2} \sum_{\Delta l} E_h(x_h, z_h) e^{-i \frac{2\pi}{\lambda} (\sqrt{(x-x_h)^2 + z_h^2})} \Delta l \]
Focal spot simulations - DiProI

32 nm wavelength

- K-B vertical best focus -2 mm from nominal FWHM_{32nm} = 5.8 \, \mu m
- K-B horizontal best focus 0 mm from nominal FWHM_{32nm} = 4.4 \, \mu m

Suggestion - the system limit in terms of the spot size should be lower than shadow predictions.
Focal spot measurements at DiProI end-station

Wave-front sensor measurements

- FEL 1
- wavelength - 32 nm
- measuring of Intensity and Wave-front at 1m out of nominal focus
- reconstruction of the spot in focal plane
**Focal spot measurements - DiProI**

**Wave-front sensor measurements**

**Fresnel diffraction simulations**

- **FEL 1**
  - Wavelength - 32 nm
  - Diffraction limit spot-size at 32 nm FWHM = 4x5 µm
  - Best spot-size measured: FWHM = 5x8 µm
  - Spot-size simulated with ray-tracing: FWHM = 10.5x18 µm
  - Spot-size simulated with Fresnel diffraction at the common best focus (-1mm from the nominal focus): FWHM = 5.2x7.7 µm
FUTURE WORK

- Characterization of the FEL wavefront by measuring the electric field with the wavefront sensor before K-B optics
- Put the measured electric field in the simulator - evaluation of the performances of the optics (degradation/improvement of the wavefront)
- Implementation of the K-B system: new anti-twisting mounting - piezo-electric actuators for mirror shape correction
CONCLUSIONS

- We performed surface profile characterization of the K-B bendable system mounted in the DiProl chamber with Long Trace Profilometer.

- We extended the Fresnel diffraction method to FEL applications - non isotropic sources - focal spot given the best measured profile at LTP - FWHM = 4.4x7.7 µm

- We provided several measurement campaigns of K-B system focalization in the DiProi end-station, 40x42 µm on the P-screen 15x26 µm on PMMA

- Through a wave-front sensor we went further in the optimization of the mirror shape. Focal spot (reconstructed via software) FWHM = 5x8 µm

- From the comparison between simulations and measures we conclude that the focal spot in a FEL can now be predicted by using the Fresnel diffraction method.
People involved in this work:

- F.Capotondi, E.Pedersoli, M.Kiskinova – DiProI
- G.Sostero – Metrology LAB
- D.Cocco – SLAC

THANKS FOR YOUR ATTENTION